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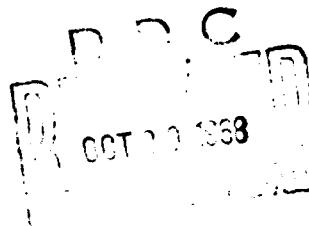
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ATMOSPHERIC EFFECTS ON DIGITALLY  
MODULATED LASER TRANSMISSION

By

Merle M. Whatley  
Donald A. Smith

July 1968



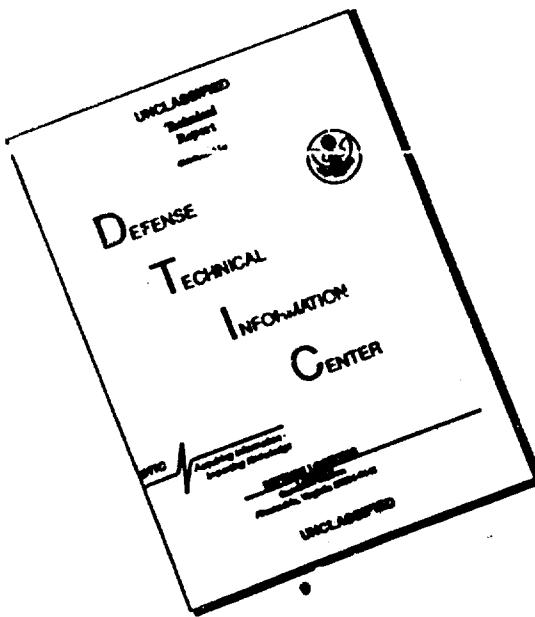
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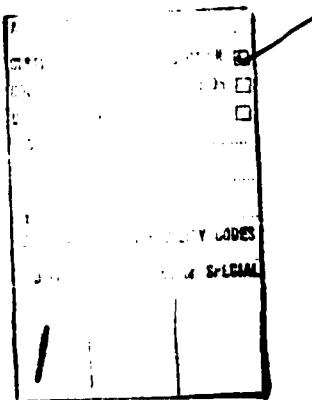
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ATMOSPHERIC EFFECTS ON DIGITALLY MODULATED  
LASER TRANSMISSION

By

Marie M. Whetley  
Donald A. Smith

Communications/AIR Laboratory

JULY 1968

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ABSTRACT

This investigation has provided data which allow the evaluation of the laser as a transmission device for digital information. In particular, the effect of the atmosphere on laser propagation, modulation, and communication capabilities pertinent to tactical applications has been studied. These studies were made under varying conditions of weather, path length, optical power, modulation depth and modulation method. The characteristic of interest in each case was the bit-error rate obtained with binary serial bit streams. From this information, the operation of a laser PCM system may be forecast.

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## ATMOSPHERIC EFFECTS ON DIGITALLY MODULATED LASER TRANSMISSION

### I. Introduction

The laser possesses several unique features which make it potentially attractive for certain military communication applications. It is particularly suitable for short-range tactical applications which require a wide bandwidth to allow a high data-transmission rate and, in addition, a high directivity to avoid interference with other units and to provide some measure of intercept security. Also, the laser offers the potential advantages of simplicity and mobility (especially when compared with multi-channel cable communication in similar applications). Finally, the use of optical frequencies should ease the burden on the crowded microwave rf spectrum.

Potential applications for a tactical laser communication system include: (1) interconnection of dispersed elements in a field computer complex; (2) connection between a hilltop microwave terminal and the switching center in a secure site below (known as the "Down-the-Hill" link); and (3) supplementary or backup communications in a microwave system. Many other applications may prove to be well-served by laser systems.

In view of the possible applications for lasers in tactical communications, an investigation was made of several pertinent factors relating to laser propagation and modulation. The investigation consisted of two general phases, the first of which included studies of atmospheric effects on laser propagation without regard to information transmission. In the second phase, the effects of the atmosphere were investigated as they influence communication. In particular, the error rates obtained with a PCM (pulse code modulation) type signal modulating the laser were measured under a variety of conditions. The error rate is directly related to the quality and reliability of communications which may be established.

### II. Preliminary Investigations

The purpose of the preliminary investigations was to examine the effects apparent in a laser beam after propagating through an atmospheric path. Of particular importance are the scintillations due to turbulence-induced refractive index inhomogeneities. The scintillations appear as multiplicative noise in a communication channel and are thus of considerable importance. The results of these tests allow comparison with those of other researchers<sup>2,3</sup> and with theoretical predictions.<sup>4</sup>

The amplitude scintillations measured over a 300-meter path under various weather conditions are shown in Figure 1. As expected, the log-amplitudes of the scintillations are normally distributed (as indicated by the straight-line distributions). It is also seen that weather has a significant effect on the distributions. The frequency spectra of the scintillations are shown in Figure 2. Most of the noise energy is contained in the 0-500 Hz band. The weather is also seen to strongly influence the frequency spectra.

FIG. 1  
Various amplitude distributions  
of atmospheric scintillations

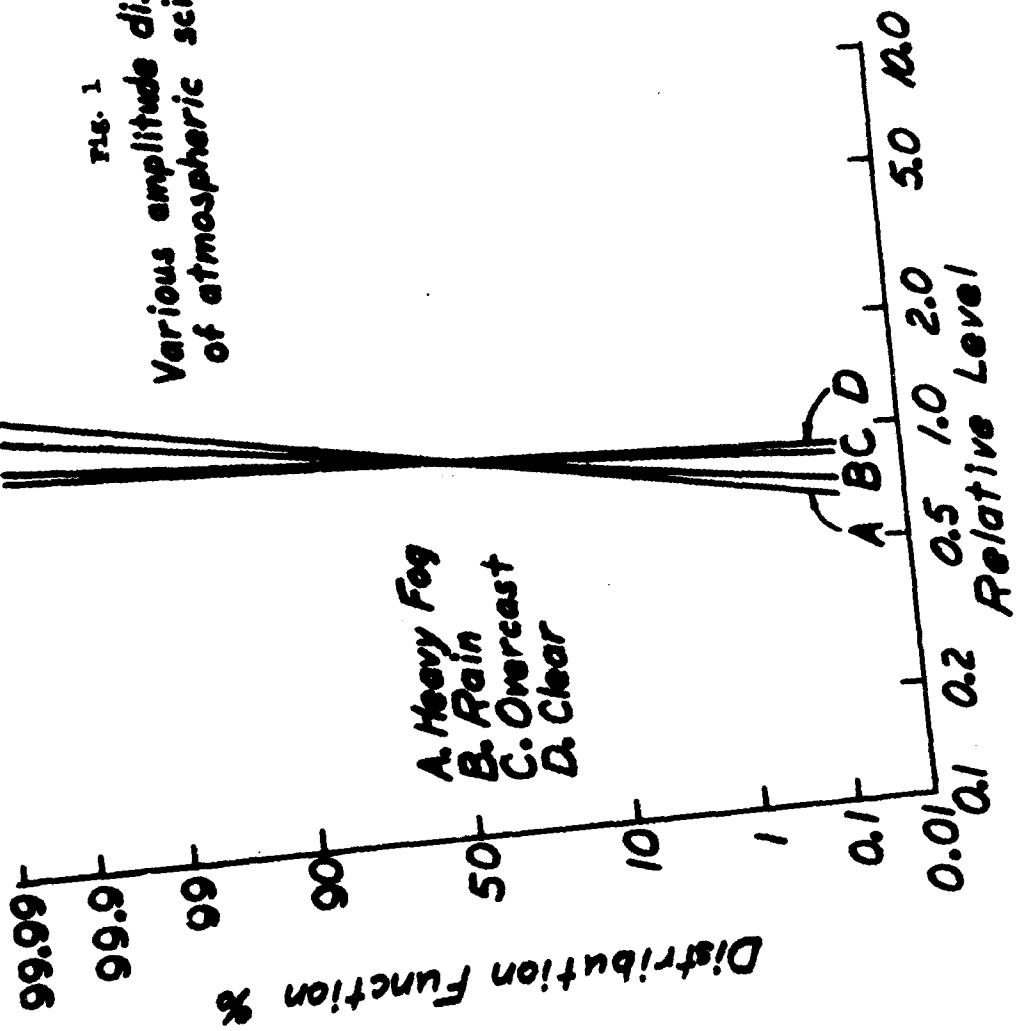
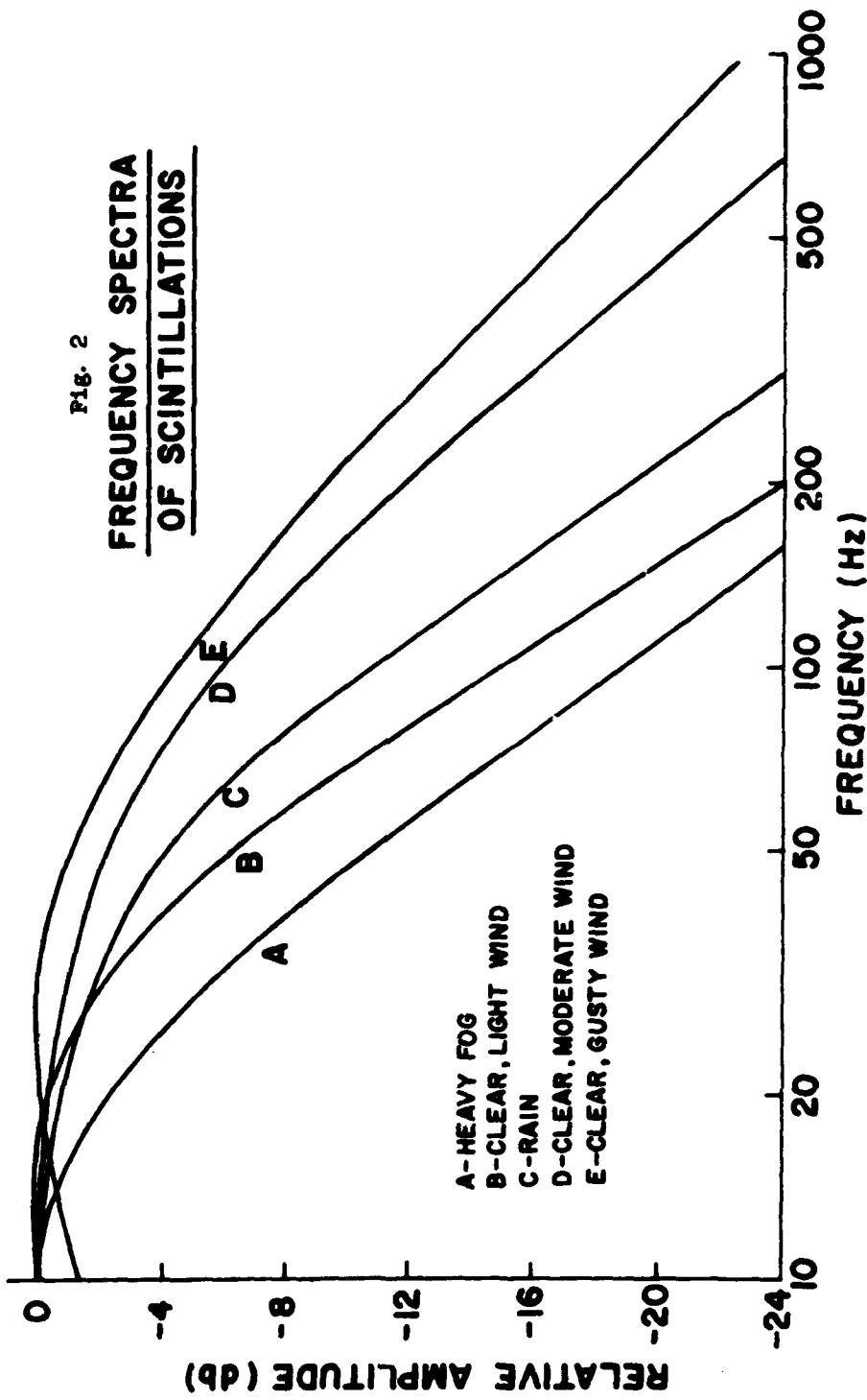


FIG. 2  
FREQUENCY SPECTRA  
OF SCINTILLATIONS



Finally, the effects of beam-movement are considered. In addition to short-term variations in beam pointing caused by turbulence, there exist larger variations having a twenty-four-hour period. These effects are evidently due to both thermal perturbations in the receiver and transmitter structure and large-scale systematic refractive index variations over the path. A typical example of the beam-pointing variations over a period of twenty-four hours is shown for a five-kilometer path in Figure 3.

The data collected in these preliminary investigations give an idea of the problems which are pertinent to communication with low-power lasers over tactical ranges. The phenomena are fairly well understood on a large-scale basis. These experiments seek to assess the range of variation to be expected under tactical conditions and, thereby, the degradation of communication to be expected.

### III. Digital Modulation Investigations

#### A. Experimental Setup

Based on the propagation experiments, a series of investigations were carried out to determine the effect of the atmosphere on a modulated laser beam and to compare various methods of modulation under varying path conditions. Particular emphasis was placed on digital transmission because of the anticipated widespread use of PCM signals and PCM multiplex equipment for military communications. The experiments were carried out in the context of tactical communication. That is, the parameters of weather, range, etc., were chosen so as to be consistent with typical field army application (rather than with space communication, optical waveguides, etc., which have been investigated elsewhere).

The digital error rate was the characteristic of principal interest in this investigation. The error rate was measured experimentally by modulating the transmitted laser beam with a digital signal and then comparing the received signal with the original on a bit-by-bit basis. The non-correspondence of a bit indicated that an error had been made in the system. The digital test signal was chosen with a bit rate approximately the same as that of current tactical PCM multiplex equipment being introduced into the military inventory. Thus the data obtained realistically predict the error probabilities of a digital laser communication link connecting current PCM equipment.

The transmitter end of the test link shown in Figure 4 consisted of a three-milliwatt HeNe laser operating at 6328 Angstroms, a KDP polarization modulator and a collimator. In addition, an analyzer could be added to allow amplitude modulation of the beam and a variable optical attenuator could be used to vary the effective optical power transmitted. The transmitted signal was directed toward a retroreflector which returned the beam to the receiver located near the transmitter.

For reception of an amplitude-modulated (AM) signal, the beam was collected by a single lens and focused onto a photodiode. The output of the photodiode was suitably isolated and amplified and fed to the error detection circuits.

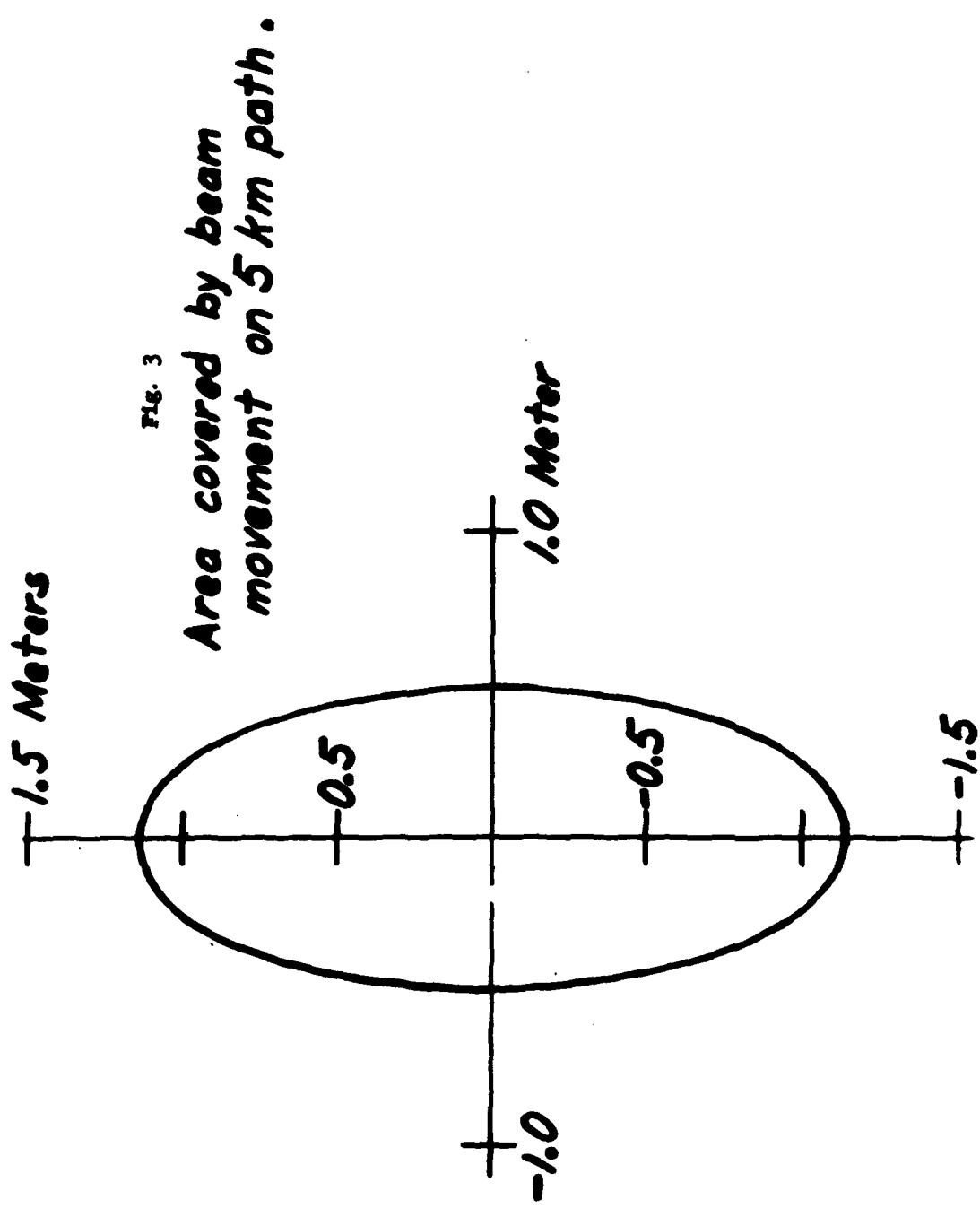
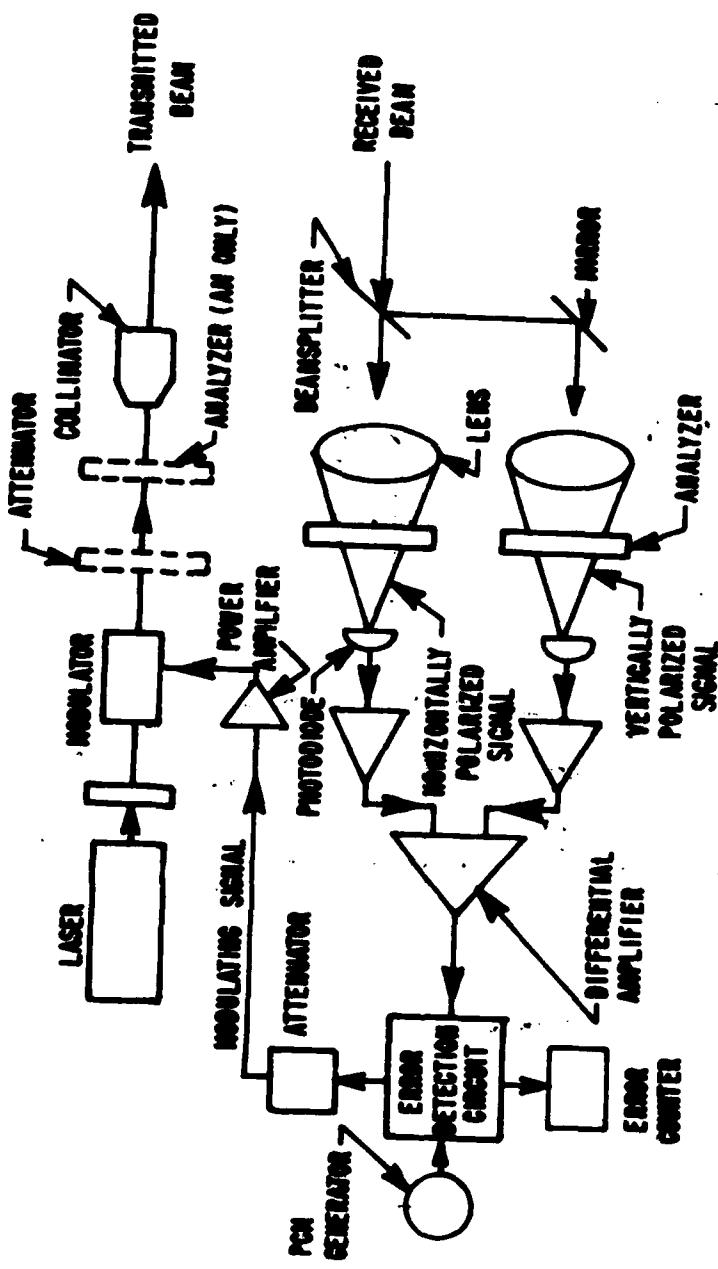


FIG. 4 LASER LINE CONFIGURATION FOR  
ECHO RATE INVESTIGATIONS



If the received signal was polarization modulated (PM), however, the receiver scheme as shown in Figure 4 was used. The beam passed through a beam splitter which divided the signal equally between two channels. Each channel consisted of a lens, an analyzer, a photodiode and an amplifier. (A Wollaston prism, of course, could have been used to accomplish the separation between channels.) The two analyzers were cross-polarized. The outputs of the two channels were fed to a differential amplifier, the output of which contained the received PCM signal.

A third configuration used at the receiver consisted of a single channel of the PM receiver (SCPM), the transmitted signal being polarization modulated as before. Obviously, this arrangement was different from the AM system only in that the analyzer was placed at the receiver instead of at the transmitter.

The electronic circuits shown in Figure 4 provided the error detection capability for the three system configurations. The received digital signal was compared to the transmitted signal (suitably delayed) in the bit comparator. Error signals, which were generated when bits were not correctly received, were recorded on the electronic counter.

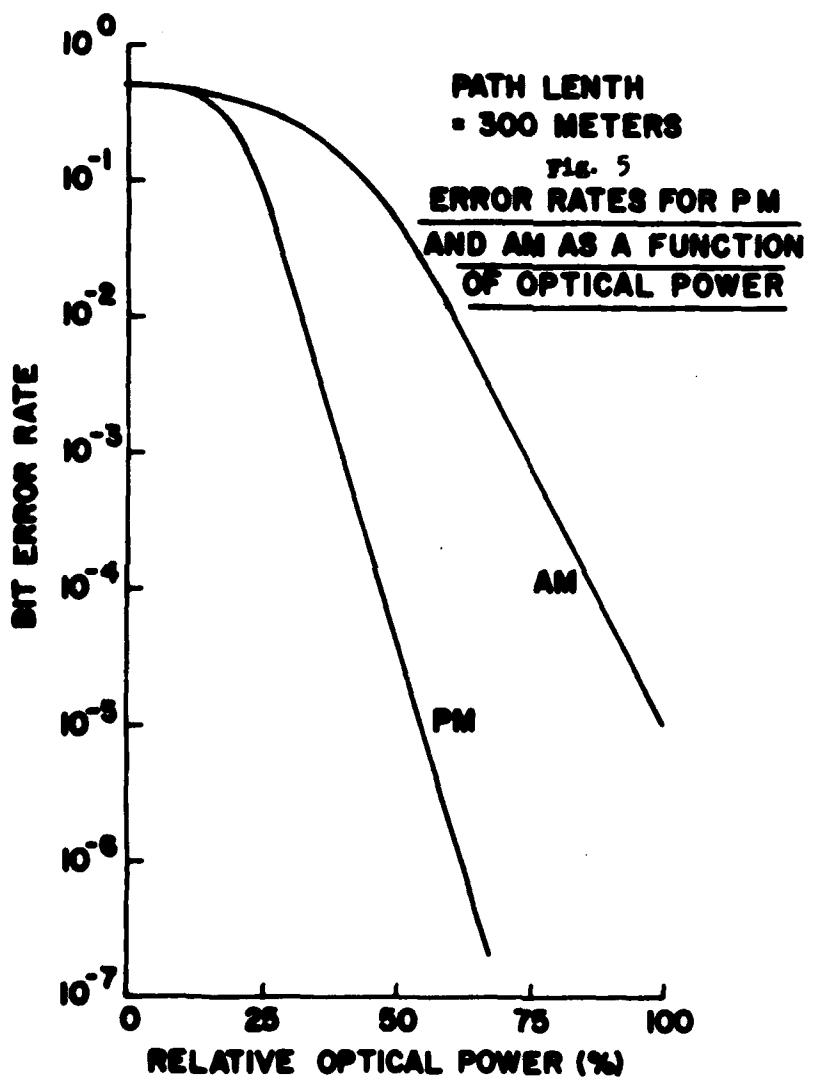
#### B. Error Rate Measurements

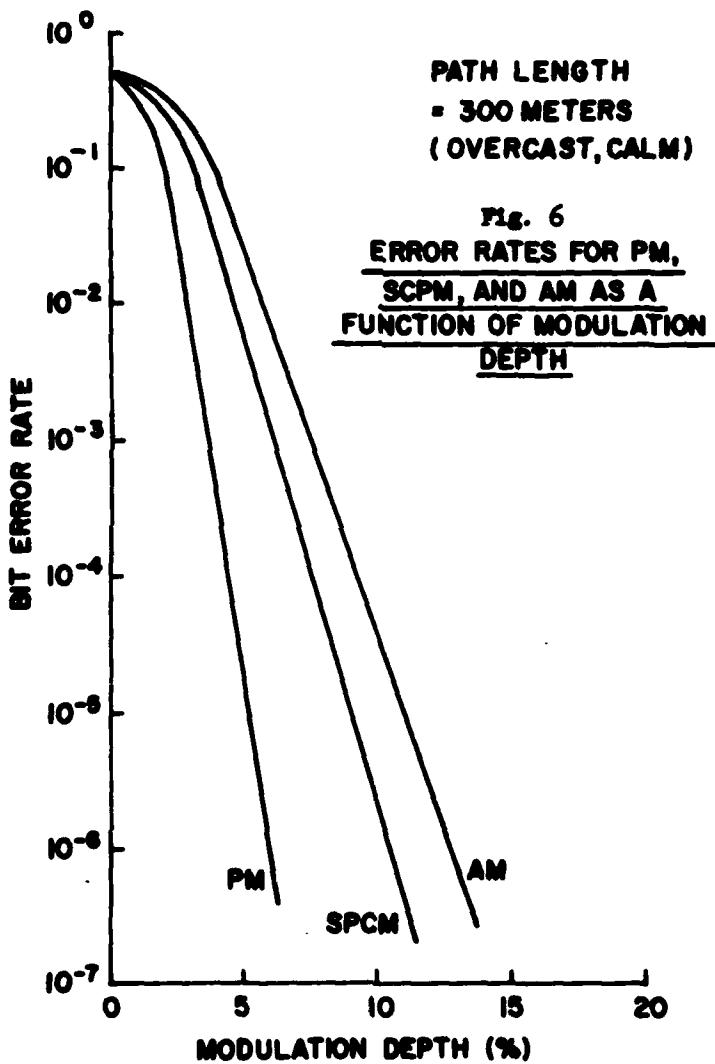
Using the experimental arrangements described above, PCM error rates were determined under various path conditions and modulator configurations.

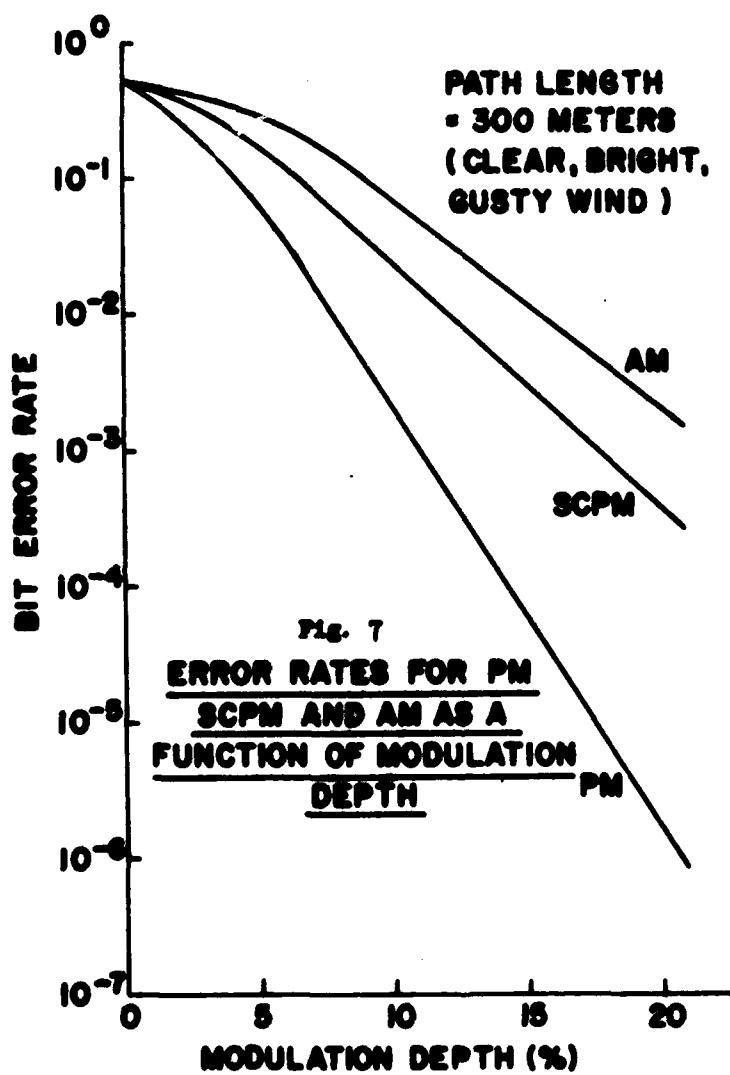
The optical power output of a laser transmitter which is required for a satisfactory bit-error rate is of great importance, especially in tactical applications, because it is closely related to the size, weight, power requirement and simplicity of the system. Figure 5 shows data which allow comparison between amplitude modulation and polarization modulation with output power as a parameter (path conditions and modulation depth are held constant). It is seen that for an error rate of  $10^{-5}$ , almost twice the laser output is required in the case of the AM system as compared to the PM system. The error rate for all power levels is obviously superior for PM.

Figures 6 and 7 allow a comparison to be made of AM, PM, and SCPM with depth of modulation as a parameter and under different atmospheric conditions. As in the case of optical power, the modulation depth which is necessary to provide an acceptable error rate is of significance because of its close relation to system size, weight, sophistication, etc. Figure 6 shows the SCPM to be superior to AM and shows PM to be superior to both. The modulation required for an error rate of  $10^{-5}$  in the PM system is approximately 5% while the SCPM requires 9% and AM requires 11%.

It is of interest to note that the weather is a critical factor in any laser system. Figure 6 shows data taken on a fairly calm, overcast day (the conditions under which scintillations are small) while Figure 7 shows data taken under identical conditions except for the weather. In the latter case, the wind was gusty and the sky was clear (conditions under which scintillation effects are the most pronounced). All three types of modulation are affected by the scintillations, however, the PM was still far superior to either SCPM or AM.







A comparison of PM error rates (Figure 8) summarizes the effects of weather. The most extreme case, taken in extremely gusty winds and under a bright sky, shows that for error rates of  $10^{-5}$  modulation depth must be at least 20%.

Finally, measurements were made in which range was a parameter. Figure 9 shows the error rate curves for PM, SCFM and AM over a one-kilometer path. The error rates were obviously much worse than at the shorter range of 300 meters. To have obtained an error rate of  $10^{-5}$  the PM system would have required approximately 40% modulation. Much higher modulation depths would have been required for SCFM and AM for the same error rate. Again the PM system was shown to be quite superior to the AM system. (The day on which these data were taken could best be described as one of moderate scintillation activity: overcast but with gusty winds.)

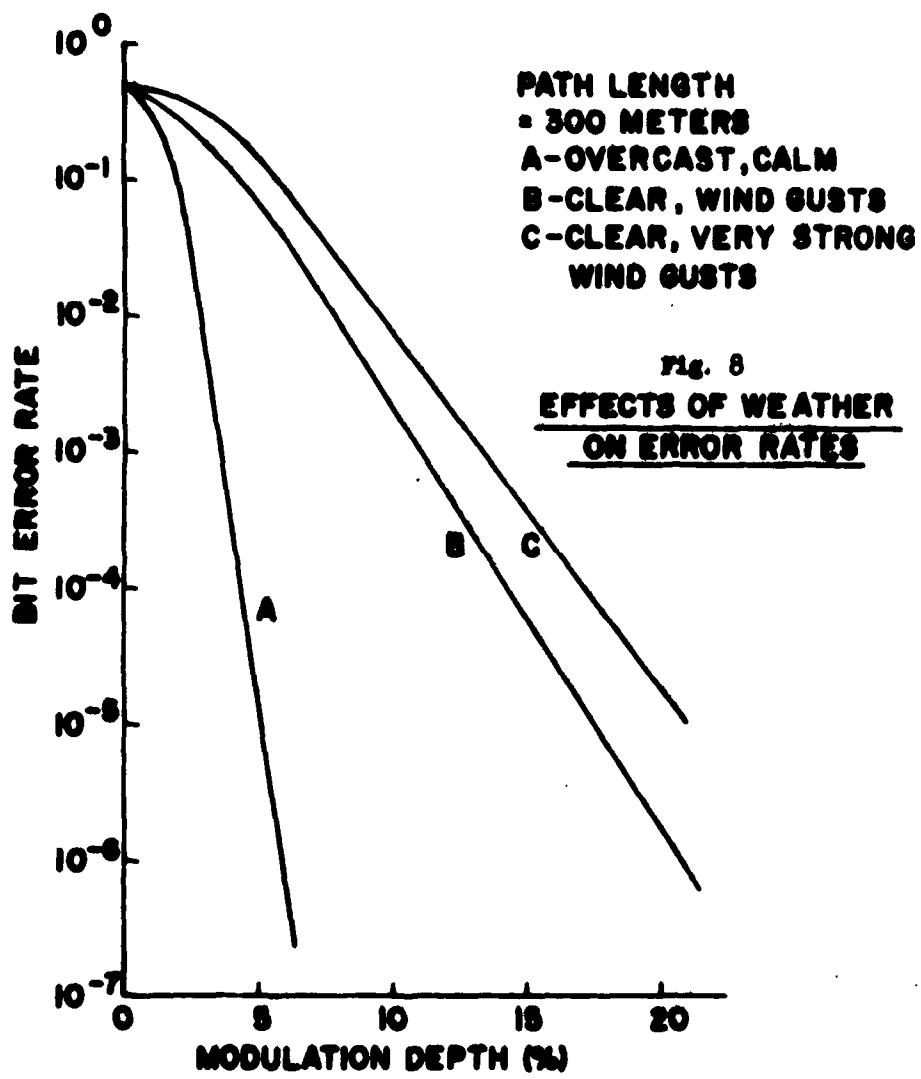
#### IV Conclusions

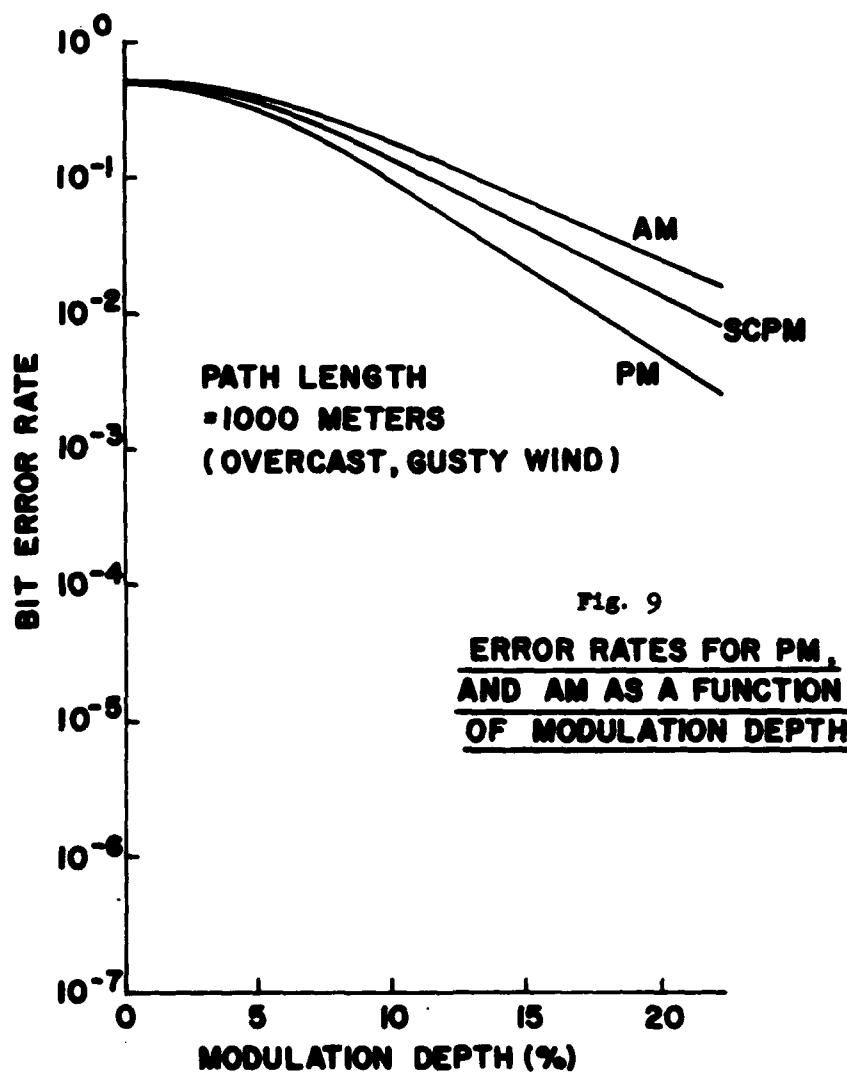
The tests which have been described provide a meaningful basis for comparison of the AM and PM systems and, in addition, point out certain trade-offs which may be made in system configuration.

At the expense of a moderate increase in complexity, the PM system exhibits a considerable superiority over the AM system in terms of error rate and the effective use of available optical power. The superiority stems from the use of two orthogonal states (e.g., vertical polarization and horizontal polarization) to represent the PCM mark and space. In contrast, in the AM system the mark and space are represented by two different values of the same state (e.g., beam amplitude). Since the atmosphere has a considerable effect on the amplitude characteristics of a laser beam and apparently very little effect on the polarization characteristics, it is to be expected that the PM system is much less susceptible to scintillation noise than AM. This expectation was verified in this investigation.

It should be pointed out that scintillation noise still exists in each channel of the PM system although its effects are to a large extent eliminated in the combining of the two channels. Almost total elimination of scintillation noise over a wide range may be accomplished by use of an intensity-sensitive AGC circuit. Such a circuit would, no doubt, be used in any practical PM communication system. The AGC is much less applicable to the AM system as intensity variations are the means of information transmission.

Although the scintillations appear as multiplicative noise, background light appears as additive noise and is present in both systems. It is to be expected, however, that the PM system will be less susceptible to unpolarized background noise than the AM system because a signal present in both channels is canceled in the combining process. The demonstrated superiority of the SCFM system over the AM system may be attributed to the partial elimination of background light provided by the analyzer when it is placed at the receiver. In most cases a narrow-band optical filter should provide sufficient reduction in background light (with some loss in the signal level).





Finally, it has been shown that compromises are possible between error rate on the one hand and optical power and/or modulation depth on the other. Thus it may be possible in specific applications to obtain satisfactory error rates with a very low-power laser and a high modulation depth, or vice versa. This factor is important in tactical applications because large modulation depths and high optical powers tend to increase requirements in size, weight, power, complexity, cooling, etc.

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